PSYCHOPHYSIOLOGY
Copyright © 1985 by The Society for Psychophysiological Research, Inc.

Vol. 22, No. 3
Printed in U.S.A.

Effects of Prolonged Sleep Deprivation, With and Without Chronic Physical Exercise, on Mood and Performance

ROBERT G. ANGUS, RONALD J. HESLEGRAVE, AND W. STEWART MYLES
Defence and Civil Institute of Environmental Medicine, Downsview, Ontario, Canada

ABSTRACT

The effects of physical exercise and sleep deprivation on mood and cognitive performance were studied in 12 healthy young male volunteers deprived of sleep on two occasions. During the first 60-hr period without sleep, half of the subjects walked on a treadmill at 25–30% of their maximum aerobic capacity (Exercise condition) for 1 out of every 3 hrs while the remaining 6 subjects remained physically inactive (No Exercise condition) during that same hour. Eight weeks later the same 12 subjects underwent an identical sleep-deprivation protocol except that those who were previously inactive exercised, while those who previously exercised remained inactive. Throughout the sleep deprivation periods, subjects in both conditions completed subjective assessments of fatigue, sleepiness and mood every 3 hrs, performed an auditory vigilance task every 6 hrs, and completed a cognitive test battery every 12 hrs. The results revealed clear decrements in mood and performance as a function of sleep loss. However, with the exception of somewhat more long reaction times in the Exercise condition, exercise neither increased nor decreased the impairment induced by sleep deprivation.

DESCRIPTORS: Sleep deprivation, Sleep loss, Exercise, Mood, Performance, Fatigue, Stress.

A number of studies have shown that decrements in mood and performance occur during and following one or more nights without sleep as well as over longer periods of reduced or fragmented sleep (for reviews see Johnson 1979; Johnson & Naitoh, 1974; Kjellberg, 1977; Naitoh, 1976; Wilkinson, 1965, 1969). The magnitude of these decrements, however, is dependent on a variety of, what Johnson (1982) has labelled, "modifier" variables, including fatigue, task-specific factors, and non-task (psychological, situational and behavioural periodicity) factors.

One non-task situational factor thought to modify sleep deprivation effects is physical exercise. However, while some studies have examined sleep loss effects in "field" settings where exercise was a major component (e.g., Bugge, Opstad, & Magnus, 1979), only two studies have experimentally assessed the extent to which exercise modifies decrements induced by sleep deprivation[1] and these studies arrived at contradictory conclusions.

The first of these studies, by Webb and Agnew (1973), suggested that exercise has minimal impact on decrements induced by sleep loss. Their subjects were deprived of sleep for approximately 48 hrs and were assigned to either Bedrest or Exercise conditions during an 8-hr period (2300h–0700h) each night. During that 8-hr period all subjects completed 2.5 hrs of performance testing. Over the remaining 5.5 hrs each night, the Bedrest subjects rested in bed while the Exercise subjects cycled on a stationary bicycle for 15 min (at 20 km/hr with a 2.5 kg friction load) on 4 separate occasions and relaxed during the remaining 4.5 hrs. One week later the Bedrest and Exercise subjects reversed roles.

Address requests for reprints to any of the authors at the following address: Defence and Civil Institute of Environmental Medicine, 1133 Sheppard Avenue West, P.O. Box 2000, Downsview, Ontario, M3M 3B9, Canada.

[1]A recent 45-hr sleep deprivation experiment by Naitoh, Englund, and Ryman (1982) is also relevant to this topic but since only preliminary analyses are available, these data will not be discussed. It should be noted, however, that the longer sleep deprivation period used in the present study (which also measured performance at the "trough" of their circadian cycles for two nights rather than one) should produce greater sleep deprivation effects than Naitoh et al. (1982).

85-6572/

The results showed that although performance was significantly impaired due to the sleep loss, neither the memory, complex addition, nor auditory vigilance tasks differentiated the Bedrest and Exercise conditions. Only a simple addition task differentiated these conditions but unexpectedly revealed a beneficial effect of exercise.

The second study, by Lubin, Hord, Tracy, and Johnson (1976), concluded that "exercise definitely increases performance decrement and sleepiness due to sleep loss" (p. 338). In that study, subjects were deprived of sleep for 40 hrs. During the first hour of each of 10 4-hr experimental epochs, the Bedrest subjects lay in bed and received biofeedback training (i.e., they attempted to either augment or suppress their EEG alpha and theta activity using auditory feedback). During that same 1-hr period, the Exercise subjects cycled at a rate that maintained a 50% increase in heart rate (HR). Although sleep deprivation resulted in significant mood and performance decrements (measured throughout each epoch), the Exercise group showed significantly greater sleepiness ratings, fewer words correctly recalled from memory, and a lower percentage of correct additions, the latter two tasks (i.e., word memory (Williams, Gieseking, & Lubin, 1966) and complex addition (Wilkinson, 1969)) being identical to those used by Webb and Agnew (1973).

Although Lubin et al. (1976) speculated that the lack of an exercise effect in the Webb and Agnew (1973) study was perhaps due to carry-over effects since the same subjects were used in both conditions, differences in energy expenditure may more parsimoniously account for the contradictory findings. In contrast to Webb and Agnew (1973), Lubin et al. (1976) exercised their subjects more (10 hrs as opposed to 2 hrs) over a shorter period of time (40 hrs vs. 48 hrs). Thus, the detrimental effect of exercise reported by Lubin et al. (1976) may simply be due to greater physical fatigue.

In light of these contradictory conclusions, the present study sought to intensify the effects of both sleep loss and exercise to maximize any potential modification of sleep loss effects by exercise. To increase the effects of sleep loss and exercise, the sleep deprivation period was extended to 60 hrs and both the frequency and total amount of exercise were increased; the frequency of exercise was increased to 1 out of every 3 hrs, which in turn increased the total amount of exercise to 20 hrs over the sleep deprivation period.

Finally, both Webb and Agnew (1973) and Lubin et al. (1976) used bedrest as a control condition, in part to examine the forced-rest hypothesis (cf., Berger, Taub, & Walker, 1973). The adequacy of this control for determining the influence of exercise during sleep loss is questionable, especially if bedrest is confounded by having subjects perform a difficult biofeedback task. Despite using this task, Lubin et al. (1976) noted that the Bedrest condition promoted drowsiness and sleep onset as evidenced by having to wake subjects one or more times during the final 16 hrs. Because bedrest promotes lowered arousal and because lower arousal can increase sleep deprivation effects (Kjellberg, 1977), such a control condition may potentiate performance decrements induced by sleep loss, thereby minimizing the differences between the control (Bedrest) and experimental (Exercise) conditions. Therefore, rather than promoting drowsiness by using a bedrest condition, the control (No Exercise) condition in the present study merely removed the physical activity by requiring that subjects engage in some cognitive but physically undemanding activities. The present control condition was intended to provide a more clear estimate of the role of exercise alone in modifying changes in mood and performance induced by sleep deprivation.

Method

Experimental Protocol

Following a number of training sessions on the cognitive tasks over several days, 12 young fit male students from the University of Toronto were deprived of sleep for 60 hrs on 2 occasions. On the first occasion of sleep deprivation, 6 subjects were randomly assigned to the Exercise condition while the remaining 6 subjects were assigned to the No Exercise condition. The subjects reversed conditions when they returned 8 weeks later. On the day preceding the second occasion of sleep deprivation, subjects were given some refresher training on the cognitive tasks used in the experiment.

Figure 1 shows the protocol for each occasion of sleep deprivation. As can be seen in the figure, the protocol effectively commenced at 1000h on Day 1 and ended at 2200h on Day 3; however, time permitted the completion of an initial set of self-report scales at 0900h on Day 1 and a single test of maximum aerobic capacity was conducted following the sleep deprivation period. In terms of the temporal arrangement of tasks, it can be seen that either exercise or rest occurred every 3 hrs starting at 1000h on Day 1. Subjective self-report and cognitive performance data were collected immediately following the exercise or rest while the auditory vigilance data were consistently collected 1 hr after the exercise or rest. In addition, the figure shows the occurrence of various physical (strength, agility, speed, and balance) tests but these results will be reported elsewhere. All tasks were presented to subjects at individual work stations and subjects were closely monitored to ensure that no unscheduled sleep was taken. If subjects were thought to be asleep they were awakened immediately.

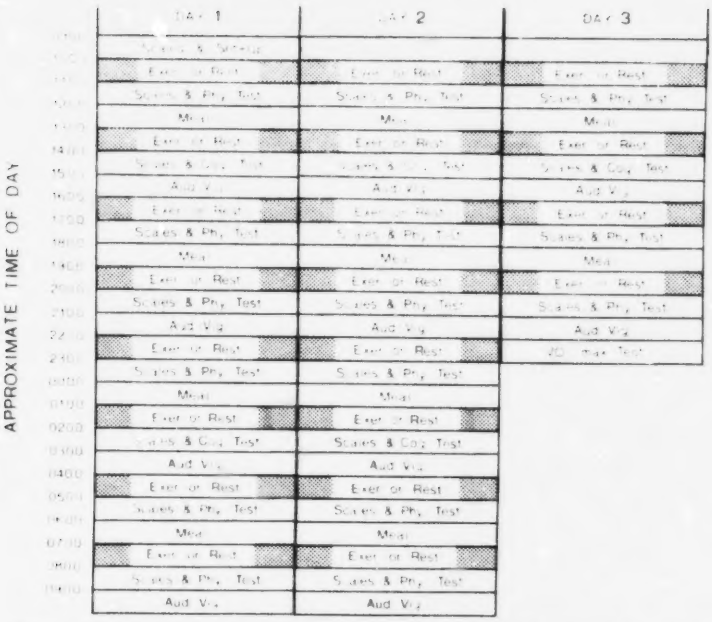

Figure 1. Experimental protocol, showing the approximate time of day of the various tasks over the 60 hrs of sleep deprivation. The protocol included Exercise or Rest periods, the completion of self-report Scales, and performance on various Cognitive, Physical, and Auditory Vigilance tasks.

Tasks

Exercise or Rest. Subjects in the Exercise condition walked on a treadmill at 25–30% of their maximum aerobic capacity ($\dot{V}O_2$ max) for 1 out of every 3 hrs for a total of 20 hrs of exercise during the experiment. The particular level of exercise used in this experiment was chosen because it was representative of more natural environments to which the present results were meant to generalize (Myles et al., 1979)[2]. The level of exercise for each subject was determined on the basis of a progressive treadmill $\dot{V}O_2$ max test (cf. Weiner & Lourie, 1969) prior to the sleep deprivation period. During the treadmill exercise in the experiment, minute-by-minute values for oxygen consumption and respiratory volume were determined using paramagnetic and infrared analyzers, a pneumotachograph, and the Jaeger "Ergo-oxyscreen," while HR was determined from a continuous ECG recording. Subjects in the No Exercise condition remained mentally occupied (e.g., watched movies, read books, studied, played games, or talked) but physically inactive while the Exercise subjects walked on the treadmill.

[2]In an investigation of energy expenditure in prolonged military marches, Myles, Eclache, and Beaury (1979) found that young, very fit soldiers adjusted their energy expenditure to 31.6% of their $\dot{V}O_2$ max and maintained this level for 6 consecutive days.

Self-Report Scales. Every 3 hrs subjects completed 3 self-report scales pertaining to their feelings of fatigue, sleepiness, and mood. The Subjective Fatigue Checklist (Harris, Pegram, & Hartman, 1971) required subjects to describe themselves in terms of energy, alertness, and fatigue (e.g., "better than," "the same as," or "worse than" such statements as "very lively," "petered out," etc.). The Stanford Sleepiness Scale (Hoddes, Zarconne, Smythe, Phillips, & Dement, 1975) required subjects to indicate their current state of sleepiness by choosing the most appropriate statement on a 7-point scale of increasing tiredness. The Mood Scale (Johnson & Naitoh, 1974) required subjects to describe their feelings of alertness, emotional state, social disposition and mood by rating themselves as either "not at all," "a little," "quite a bit," or "extremely" in relation to 19 positive adjectives (e.g., active, considerate, happy) and 10 negative adjectives (e.g., tense, sluggish, jittery).

Auditory Vigilance. At 6-hr intervals subjects were presented with a 1-hr Auditory Vigilance task over headphones (Colquhoun, Hamilton, & Edwards, 1974). The task involved detecting the presence of "signals" (i.e., 500-ms, 1000 Hz, 45dB SPL tones) that were superimposed on a 3-s burst of wideband noise (approximately 85dB SPL) 1 s prior to its offset. Signals occurred on about 10% of the trials in a pseudorandom fashion. Each 3-s burst of 85dB noise alternated with a 3-s burst of 80dB noise during which signals were

never presented. Subjects were also instructed that signals would only occur during the more intense noise trials. Correct detections and missed signals were scored.

Cognitive Tasks. Every 12 hrs subjects were tested for 10 min on paper and pencil versions of each of the following tasks: Logical Reasoning, Visual Search, Mental Addition, and Encoding/Decoding. In addition, they were also tested for 15 min on an automated 4-Choice Serial Reaction Time task. For all tasks, subjects were instructed to perform as quickly and as accurately as possible.

The Logical Reasoning task (Baddeley, 1968) required subjects to evaluate the veracity of statements, varying in their syntactic complexity (e.g., "A comes before B" or "B does not precede A"), with reference to an associated letter pair (e.g., "AB" or "BA"). The Visual Search Task (Fort & Mills, 1972) required subjects to locate an average of 15 (range 10–25) repeated letters (e.g., "TT" or "BB") in blocks of 450 randomly arranged capital letters. The Mental Addition Task (Wilkinson, 1969) required subjects to add as many columns of 5, 2-digit numbers as they could in the 10-min period. The Encoding/Decoding Task (Haslam, 1983) required subjects to translate 6-digit map grid references into 4-letter codes (Encode) or the reverse (Decode) by a set of rules.

The 15-min 4-Choice Serial Reaction Time Task (Wilkinson & Houghton, 1975) required subjects to attend to an apparatus containing 4 stimulus lights and 4 corresponding buttons. The lights were illuminated one-at-a-time in a random fashion and the subjects' task was to extinguish each light by pressing the spatially corresponding button. The onset of each light immediately followed a button press to a preceding light. Total number of responses, errors, and gaps (defined as reaction times exceeding 1000 ms) were recorded.

Results

Changes in self-report, auditory vigilance, and cognitive performance were analyzed for this repeated measures design using analysis of variance with sleep deprivation (i.e., time) and exercise as factors, while changes in the physiological responses to exercise are reported as a function of sleep deprivation. The order of treatment (i.e., Exercise followed by No Exercise or the reverse) was originally included as a factor in the analyses to check for systematic changes that may have been attributable to order. Since this factor did not influence the results, the analyses reported do not include treatment order as a factor. Finally, since the design used in this study is a repeated measures design, the assumption of homogeneity of population variance-covariance matrices is likely violated and the resulting F tests are likely positively biased. In order to minimize the influence of violations of homogeneity, conservative F tests were conducted by maximally reducing the degrees of freedom to their theoretical minimum using the technique suggested by Geisser and Greenhouse (1958) (see Winer, 1971).

Self-Report Scales

As the sleep deprivation period continued, subjects in both the Exercise and No Exercise conditions reported that their subjective assessments of fatigue, sleepiness, and mood became increasingly more negative[3] (Figures 2–5). Specifically, subjects reported feelings of increased fatigue ($F(1/11) = 35.85$, $MS_e = 4.99$, $p<.001$), more sleepiness ($F(1/11) = 36.44$, $MS_e = 0.464$, $p<.001$), reduced positive mood ($F(1/11) = 25.58$, $MS_e = 30.36$, $p<.001$), and increased negative mood ($F(1/11) = 31.49$, $MS_e = 5.75$, $p<.001$). In general, the changes in subjective states became increasingly negative

[3]Figures 2–5 also include the initial set of scales completed at 0900h on Day 1.

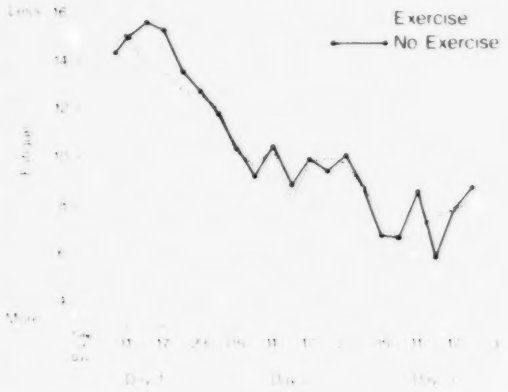

Figure 2. Increases in Fatigue ratings for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

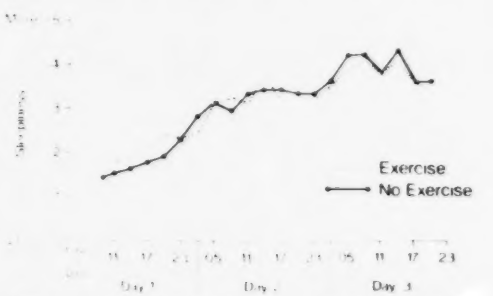

Figure 3. Increases in Sleepiness ratings for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

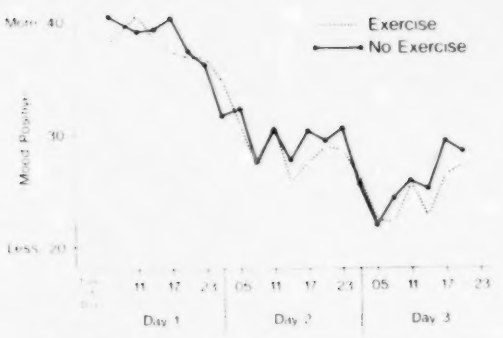

Figure 4. Declines in Positive Mood ratings for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

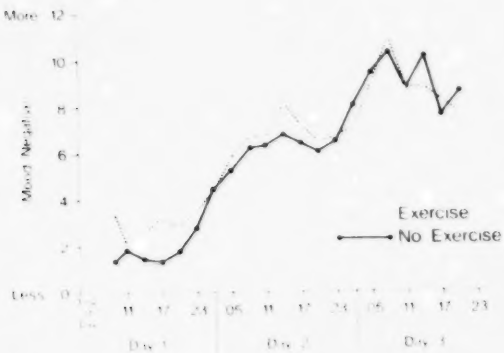

Figure 5. Increases in Negative Mood ratings for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

during the first 24 hrs, followed by a plateau until about 2300h of the second night, after which still greater negative feelings emerged. However, there were no statistically significant differences between the Exercise and No Exercise conditions.

Auditory Vigilance

As can be seen in Figure 6, the percentage of correct detections for both the Exercise and No Exercise conditions changed significantly over the sleep deprivation period ($F(1/11) = 29.50$, $MS_e = 207.30$, $p<.001$). The pattern of change was similar to that observed for the self-report scales in that there was a drop in performance during the first night, followed by plateaued performance until 0300h of the second night, and then a further decrease. As was the case with the self-report data, the Exercise and No Exercise conditions did not differ significantly ($F = 1.14$) nor did they change differentially over the sleep deprivation period ($F = 1.39$).

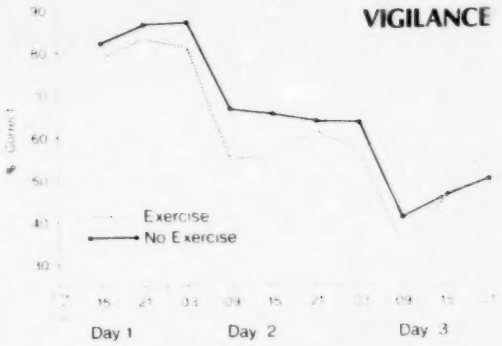

Figure 6. Declines in percentage of correct detections in a 1-hr Auditory Vigilance task for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

Cognitive Tasks

Apart from a single exception, there were no differences between the Exercise and No Exercise conditions on any of the cognitive tasks. Since errors on the 10-min tasks did not change significantly, Table 1 shows the pooled mean number correct for each of the 10-min tasks over the course of the experiment. As can be seen, performance became significantly impaired over the sleep deprivation period on the Logical Reasoning ($F(1/11) = 12.01$, $MS_e = 450.74$, $p<.01$), Visual Search ($F(1/11) = 7.77$, $MS_e = 39.28$, $p<.025$), Mental Addition ($F(1/11) = 8.48$, $MS_e = 67.60$, $p<.025$), and Encoding/Decoding ($F(1/11) = 16.44$, $MS_e = 21.11$, $p<.01$) tasks. Figure 7 shows the significant decrement in performance on the 15-min Serial Reaction Time task ($F(1/11) = 15.33$, $MS_e = 133.98$, $p<.01$) in terms of percentage of correct responses since both the number of correct responses and errors changed over the course of the experiment. These data show a pattern of change resembling the pattern reported for other tasks, i.e., stable performance until after 0200h of the first night, followed by reduced performance during the next 24 hrs, and a further reduction by 1400h of the final day.

Table 1

Mean number correct for all 10-min cognitive tasks over 60 hrs of sleep loss

	Mean Number Correct			
Times of Testing	**Logical Reasoning**	**Visual Search**	**Mental Addition**	**Encoding/ Decoding**
1400	205.87	71.87	53.04	34.00
0200	217.54	73.08	53.08	34.83
1400	196.00	66.42	45.62	29.12
0200	193.91	69.33	46.54	28.96
1400	177.08	64.62	41.96	25.75

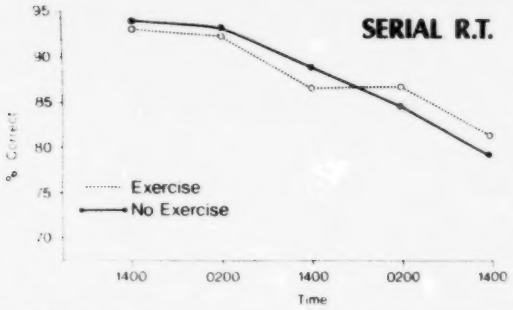

Figure 7. Declines in percentage of correct responses in a 15-min Serial Reaction Time task for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

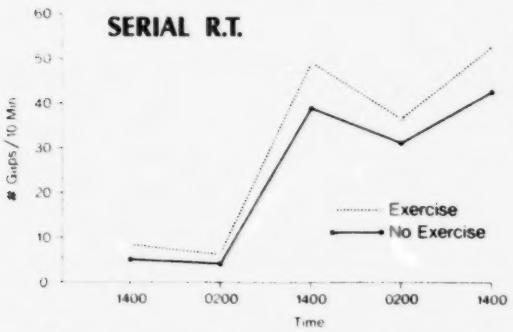

Figure 8. Increases in the number of gaps (reaction times exceeding 1000 ms) in a 15-min Serial Reaction Time task for both Exercise and No Exercise conditions over 60 hrs of sleep loss.

The Serial Reaction Time data were also analyzed in terms of the number of gaps, i.e., reaction times exceeding 1000 ms in duration, since such gaps (or "blocks" or "lapses") have been shown to be sensitive to sleep deprivation (Naitoh & Townsend, 1970; Wilkinson, 1959; Williams, Lubin, & Goodnow, 1959). While Figure 8 shows that expected significant increases in the number of gaps occurred as a function of sleep deprivation ($F(1/11) = 29.12$, $MS_e = 255.91$, $p<.001$), these data also revealed that the Exercise condition showed significantly more gaps than the No Exercise condition ($F(1/11) = 5.14$, $MS_e = 177.59$, $p<.05$).

Physiological Responses to Exercise

The goal of having subjects exercise between 25–30% of the $\dot{V}O_2$ max was achieved since subjects exercised at an average of 28% of their $\dot{V}O_2$ max. In addition, it was found that neither their oxygen consumption ($\overline{X}$ = 1.03 liters/min), nor their respiratory volume ($\overline{X}$ = 24.8 liters/min), nor their HR ($\overline{X}$ = 100 bpm) levels changed over the sleep deprivation period.

Discussion

In contrast to Lubin et al. (1976), we must conclude from our results that moderate and regular exercise does not modify sleep deprivation effects to any great extent. Despite the fact that both the sleep deprivation period and the frequency and total amount of exercise were increased relative to Lubin et al. (1976), and that a neutral control condition was used rather than one that may have potentiated sleep loss effects (cf. Kjellberg, 1977), the Exercise and No Exercise subjects did not differ in terms of their subjective states or their ability to perform tasks demanding vigilance or complex cognitive skills. These results support the earlier assertion by Webb and Agnew (1973) and are consistent with a more recent suggestion by Naitoh, Englund, and Ryman (1983).

Although the conclusion from the present study is in direct opposition to that of Lubin et al. (1976), careful examination of that study suggests that their results are equivocal. Of the three measures indicating significantly greater sleep loss effects in the Exercise condition, compared to the Bedrest condition, two of them (sleepiness and memory) were anomalies in several ways, as noted by the authors. One anomaly was that both measures revealed significant impairment in a third group that was permitted to "nap" every 4 hrs, a group which should have been unimpaired because they received regular opportunities for sleep. (The "Nap" group was, in fact, unimpaired on all the remaining measures.) Further, the impairment in the "Nap" group on these measures *exceeded* that observed in the Bedrest group, a result opposite to that expected. Finally, the remaining complex addition task purportedly showed greater impairment in the Exercise condition compared to the Bedrest condition. However, the better performance in the Bedrest condition did not interact with the sleep loss effect (see Lubin et al., 1976, Figure 1). In other words, a sampling bias resulted in better performers on this task being assigned to the Bedrest condition; the Bedrest condition showed almost parallel performance decrements to the Exercise condition (although at a higher level of performance). Thus, there is no clear evidence from the Lubin et al. (1976) study that exercise modifies sleep deprivation effects.

The lack of an exercise effect in the present study may be attributed to the fact that the exercise was moderate in intensity and regular in occurrence. Perhaps more exhaustive and/or continuous exercise might increase general fatigue and the necessity for sleep which, in turn, might modify (i.e., increase) sleep deprivation effects on performance (i.e., degrade performance). It may be that when exercise

intensity, frequency or duration are increased sufficiently to alter the physiological responses to a constant workload, which did not occur in the present study, exercise may then influence cognitive performance changes induced by sleep loss.

To conclude, the present results do not support the common-sense view that prolonged moderate exercise increases the deterioration in mood and performance that accompanies sleep loss. However, other effects of exercise have yet to be fully explored. For instance, another effect commonly attributed to exercise is that short-duration periods of exercise occurring during periods of poor performance may provide some relief from mood and performance decrements induced by sleep loss. This view is characterized well by Wilkinson (1965) who stated, "it has often been observed incidentally that the best way to revive a flagging subject is to take him for a walk or otherwise exercise him physically" (p. 418). Regardless of the appeal of this suggestion, there is little empirical evidence to support such a view. The beneficial effect of such short-term contingent exercise is an important topic awaiting rigorous investigation.

REFERENCES

Baddeley, A.W. (1968). A 3 minute reasoning test based on grammatical transformation. *Psychonomic Science, 10,* 341–342.

Berger, R.J., Taub, J.M., & Walker, J.M. (1973). Sleep as a biological adaptive process. In U.J. Jovanovic (Ed.), *The nature of sleep* (pp. 252–255). Stuttgart: Fischer.

Bugge, J.F., Opstad, P.K., & Magnus, P.M. (1979). Changes in the circadian rhythm of performance and mood in healthy young men exposed to prolonged, heavy physical work, sleep deprivation, and caloric deficit. *Aviation, Space, and Environmental Medicine, 50,* 663–668.

Colquhoun, W.P., Hamilton, P., & Edwards, R.S. (1974). *Signal detection efficiency in the morning watch* (Royal Naval Report 10/74). London: Royal Navy Personnel Research Committee.

Fort, A., & Mills, J.N. (1972). Influences of sleep, lack of sleep, and circadian rhythm on short psychometric tests. In W.P. Colquhoun (Ed.), *Aspects of human efficiency* (pp. 115–127). London: The English Universities Press.

Geisser, S., & Greenhouse, S.W. (1958). An extension of Box's results on the use of the *F* distribution in multivariate analysis. *Annals of Mathematical Statistics, 29,* 885–891.

Harris, D.A., Pegram, G.V., & Hartman, B.O. (1971). Performance and fatigue in double-crew transport missions. *Aerospace Medicine, 42,* 980–986.

Haslam, D.R. (1983). The incentive effect and sleep deprivation. *Sleep, 6,* 362–368.

Hoddes, E., Zarconne, V., Smythe, H., Phillips, R., & Dement, W.C. (1975). Quantification of sleepiness: A new approach. *Psychophysiology, 10,* 431–436.

Johnson, L.C. (1979). *Sleep disturbances and performance* (NATO AGARD Lecture Series No. 105, pp. 8:1–8:17). Paris: NATO Advisory Group for Aerospace Research and Development.

Johnson, L.C. (1982). Sleep deprivation and performance. In W. B. Webb (Ed.), *Biological rhythms, sleep, and performance* (pp. 111–141). Chichester, England: John Wiley and Sons.

Johnson, L.C., & Naitoh, P. (1974). *The operational consequences of sleep deprivation and sleep deficit* (NATO AGARDograph No. 193). Paris: NATO Advisory Group for Aerospace Research and Development.

Kjellberg, A. (1977). Sleep deprivation and some aspects of performance: I–III. *Waking and Sleeping, 1,* 139–155.

Lubin, A., Hord, D.J., Tracy, M.L., & Johnson, L.C. (1976). Effects of exercise, bedrest and napping on performance decrement during 40 hours. *Psychophysiology, 13,* 334–339.

Myles, W.S., Eclache, J.P., & Beaury, J. (1979). Self-pacing during sustained, repetitive exercise. *Aviation, Space, and Environmental Medicine, 50,* 921–924.

Naitoh, P. (1976). Sleep deprivation in human subjects: A reappraisal. *Waking and Sleeping, 1,* 53–60.

Naitoh, P., Englund, C.E., & Ryman, D. (1982). *Restorative power of naps in designing continuous work schedules* (NHRC Technical Report 82-25). San Diego: Naval Health Research Center.

Naitoh, P., Englund, C.E., & Ryman, D. (1983). *Extending human effectiveness during sustained operations through sleep management* (NATO Defence Report DS/A/DS(83) 170, Vol. 1, pp. 113–137). Toronto: NATO Defence Research Group.

Naitoh, P., & Townsend, R.E. (1970). The role of sleep deprivation research in human factors. *Human Factors, 12,* 575–585.

Webb, W.B., & Agnew, H.W. (1973). Effects of performance on high and low energy-expenditure during sleep deprivation. *Perceptual and Motor Skills, 37,* 511–514.

Weiner, J.S., & Lourie, J.A. (1969). *Human biology: A guide to field methods.* Oxford, U.K.: Blackwell.

Wilkinson, R.T. (1959). Rest pauses in a task affected by lack of sleep. *Ergonomics, 2,* 373–380.

Wilkinson, R.T. (1965). Sleep deprivation. In O.G. Edholm & A. Bacharach (Eds.), *The physiology of human survival* (pp. 399–430). New York: Academic Press.

Wilkinson, R.T. (1969). Sleep deprivation: Performance tests for partial and selected sleep deprivation. In L.E. Abt & B.F. Riess (Eds.), *Progress in clinical psychology* (Vol. 8, pp. 28–43). New York: Grune and Stratton.

Wilkinson, R.T., & Houghton, D. (1975). Portable four-choice reaction time test with magnetic tape memory. *Behavioural Research Methods and Instrumentation, 7,* 441–446.

Williams, H.L., Lubin, A., & Goodnow, J.J. (1959). Impaired performance with acute sleep loss. *Psychological Monographs: General and Applied, 73,* 1–26.

Williams, H.L., Gieseking, C.F., & Lubin, A. (1966). Some effects of sleep loss on memory. *Perceptual and Motor Skills, 23,* 1287–1293.

Winer, B.J. (1971). *Statistical principles in experimental design.* New York: McGraw-Hill.

(Manuscript received April 20, 1984; accepted for publication October 3, 1984)